A Nuclear Data Approach for the Hubble Constant Measurements

B. Pritychenko

National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY 11973-5000

ABSTRACT

An extraordinary number of Hubble constant measurements challenges physicists with selection of the best numerical value. The standard U.S. Nuclear Data Program (USNDP) codes and procedures have been applied to resolve this issue. The nuclear data approach has produced the most probable or recommended Hubble constant value of 66.2(77) (km/sec)/Mpc. This recommended value is based on the last 25 years of experimental research and includes contributions from different types of measurements. The present result implies $(14.78\pm1.72)\times10^9$ years as a rough estimate for the age of the Universe. The complete list of recommended results is given and possible implications are discussed.

Subject headings: cosmology: observations — methods: data analysis

1. Introduction

The Hubble constant and its present-day numerical value play an important role in modern astrophysics and cosmology (Boyd 2008; Dolgov et al. 1988). For many years, researchers have been improving the accuracy of the constant (Livio, Riess 2013). Fig. 1 shows the time evolution of Hubble research in the last 100 years, and the original effort can be traced as early as 1916 (Huchra et al. 2015). The large number of measurements creates a certain degree of confusion about Hubble constant numerical value, and scientists often rely on recently-published results (Particle Data Group 2014). The precision of Hubble constant measurements has improved enormously over the years; however, it is not always prudent to reject older results in favor of the latest findings. Consequently, it makes perfect sense to analyze all available results, evaluate the data, and extract the recommended value.

2. Hubble Constant Evaluation

The volume of Hubble constant measurements far exceeds other experimental quantities in physics (Pritychenko 2015). Previously, similar situations have been encountered in nuclear and particle physics and resolved with data evaluations. Nuclear data evaluations and their policies are well described in literature (Pritychenko et al. 2012; ENSDF 2015). Frequently, the evaluations are completely based on or adjusted to available experimental data. These adjustments and specialized mathematical statistics techniques can be applied for nuclear, particle, or any other data sets.

In this work, I would follow standard nuclear data evaluation procedures to deduce the recommended value. Current evaluation input data are mostly based on the NASA/HST Key Project on the Extragalactic Distance Scale compilation (Huchra et al. 2015) and recent results. A visual inspection of historical Hubble Constant measurements, as shown in Fig. 1, is instrumental in the data analysis. It suggests that one may safely reject all measurements prior to 1970. It is common knowledge that Hubble constant measurements heavily rely on the accuracy of astronomic distance determination. Older results, such as those reported by A. Sandage and G. de Vancouleurs, suffered from inaccurate measurements (Livio, Riess 2013). Therefore, the rejection of all results prior to 1990 could provide a complimentary benchmark value of the Hubble constant.

In the present data analysis, the experimental data have been separated into two groups, with 1970 and 1990 time cuts, and further reduced us-

ing the following policies:

- Rejection of repeated results (multiple publication of the same result)

- Rejection of model-dependent results (i.e. Cosmic Microwave Background (CMB) fits)

- Rejection of potential outliers using Chauvenet's criterion (Birch, Singh 2014)

Common data evaluation practices indicate that recommended value should be based on a large statistical sample that includes different types of measurements. The 1970 and 1990 redacted data sets of $\sim$334 and $\sim$266 data points, respectively, provide such samples. These large samples create the possibility of deducing Hubble constant value for each method of observation besides the combined value that is based on all measurements. The current data collections were further subdivided using a NASA/HST Key Project on the Extragalactic Distance Scale classification of experimental methods (Huchra et al. 2015):

- S = Type Ia supernovae (SNIa)

- 2 = Type II supernovae (SNII)

- L = Lens

- r = Red Giants

- B = Baryonic Tully-Fisher

- R = Inverse Tully-Fisher (ITF,RTF)

- H = Infrared Tully-Fisher (or IRTF)

- F = Fluctuations

- A = Global Summary

- Z = Sunyaev-Zeldovich

- T = Tully-Fisher

- O = Other

These experimental data sets have been processed with the latest version of the visual averaging library (Birch, Singh 2014). The library program includes limitation of relative statistical weight (LWM), normalized residual (NRM), Rajeval technique (RT), and the Expected Value

(EVM) statistical methods to calculate averages of experimental data with uncertainties. The experimental data sets were processed, and evaluated values with reduced $\chi^2 < 2$ were typically accepted as reasonable data fits. The current evaluation incorporates statistical methods based on the inverse squared value of the quoted uncertainties, a procedure that is consistent with the general methodology used in treatment of data for the ENSDF database (ENSDF 2015) and Particle Data Group (Particle Data Group 2014).

3.   Results and Discussion

Two sets of recommended values are displayed in Fig. 2, and the combined numerical values are shown in Table 1. The Hubble constant combined central values extracted by means of different mathematical techniques are in good agreement, while uncertainties need further discussion. Visual inspection of the numerical values shown in the Fig. 2 indicates the Best Representation mathematical procedure (depicted as "BR") provides a best fit for different experimental methods with reasonable uncertainties. Other procedures such as the Bootstrap technique (depicted as "Bs") result in rather small uncertainties. These small uncertainties are due to specifics of data analysis procedures such as assignment of different statistical weights to results with different uncertainties. In light of this disclosure, it is prudent to select the Best Representation results as the recommended value. The current results are consistent with the recent Particle Data Group publication (Particle Data Group 2014).

Finally, two different time cuts of 1970 and 1990 for Hubble's data have yielded two recommended values of 66.2(89) and 66.2(77) (km/sec)/Mpc, respectively. The agreement between these values partially reflects the fact that the majority of the Hubble's constant measurements has been performed in the last 25 years, and a small number of potential outliers has been rejected. More accurate recent observations imply a preference for the 1990 time cut value of 66.2(77) (km/sec)/Mpc. The last result is consistent with the Hubble Space Telescope and Wide Field Camera 3 (Riess 2011) and the model-dependent Planck's Mission and WMAP values (Bucher 2013; Bennett 2013). Inclusion of the globular cluster luminosity function,

Dn-Sig/Fund Plane, Novae and planetary nebula luminosity function data would slightly change 1970 and 1990 recommended values to 66.9(90) and 66.9(78), respectively. These less precise measurements do not affect the recommended values severely because of a Chauvenet's criterion analysis.

In recent years, an effort has been made to calculate the Hubble constant median statistics (Chen, Ratra 2011). The median statistics approach differs substantially from the nuclear or particle data evaluation procedures. At the same time, it provides a complementary value of 68±5.5 (or ±1) (km/sec)/Mpc (Chen, Ratra 2011) that can be compared with the present results.

The knowledge of Hubble constant value has multiple implications in science. As an example, a rough estimate of the age of the Universe can be deduced using the standard methodic (Wikipedia 2015). The adopted value of 66.2(77) (km/sec)/Mpc implies $(14.78 \pm 1.72) \times 10^9$ years estimated value for the age of Universe. The last result is consistent with the recently published value of $(13.798 \pm 0.037) \times 10^9$ years (Planck 2014).

4. Conclusions

The analysis of Hubble constant measurements has been performed using standard USNDP codes and procedures. An evaluated data set of most probable values of Hubble constant has been deduced and shown in the Table 1. These values are consistent with other available results. An accurate constant value is instrumental for many potential applications. The recommended value of the constant is completely based on experimental measurements, and further, more precise observations, would lead to more accurate determination of it.

REFERENCES

Boyd, R.N., AN INTRODUCTION TO NUCLEAR ASTROPHYSICS. The University of Chicago Press, Chicago and London (2008). ISBN-10: 0-226-06971-0, ISBN-13: 978-0-226-06971-5.

Dolgov, A.D., Zel'dovich, Ya. B., Sazhin, M.V., COSMOLOGY OF THE EARLY UNIVERSE. The University of Moscow Press, Moskva (1988). In Russian. ISBN 5-211-00108-7.

Livio, M., Riess, A.G., PHYSICS TODAY, October 2013, 41 (2013).

Huchra, J., THE NASA/HST KEY PROJECT ON THE EXTRAGALACTIC DISTANCE SCALE, https://www.cfa.harvard.edu/dfabricant/huchra/hubble.plot.dat; downloaded May 19, 2015.

Pritychenko, B., J. PHYS. G: NUCL. PART. PHYS. **42,** 075103 (2015).

Pritychenko, B., Choquette, J., Horoi, M., Karamy, B., Singh, B., ATOMIC DATA AND NUCLEAR DATA TABLES **98,** 798 (2012).

EVALUATED NUCLEAR STRUCTURE DATA FILES (ENSDF), http://www.nndc.bnl.gov/ensdf, downloaded May 24, 2015; Burrows, T.W., NUCL. INSTR. AND METH. **A 286,** 595 (1990).

Birch, M., Singh, B., NUCLEAR DATA SHEETS **120**, 106 (2014).

Olive, K.A.,et al. (Particle Data Group), CHIN. PHYS. **C 38**, 090001 (2014).

Riess, A.G., et al, ARXIV:1103.2976 (2011).

Chen, G., Ratra, B, ARXIV:1105.5206 (2011).

Bucher, P. A. R. et al. (Planck Collaboration) (2013). arXiv:1303.5062 [astro-ph.CO].

Bennett, C. L. et al. (2013). The Astrophysical Journal Supplement Series **208 (2)**: 20. arXiv:1212.5225.

Wikipedia: Hubble's law, http://en.wikipedia.org/wiki/Hubble%27s_law; downloaded May 19, 2015.
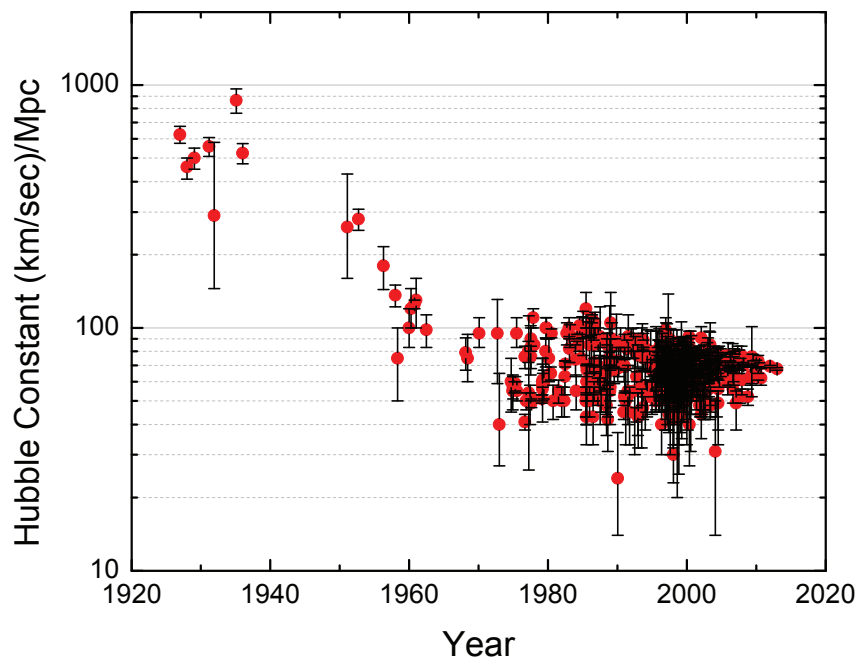
Planck Collaboration A&A **571,** A1 (2014).

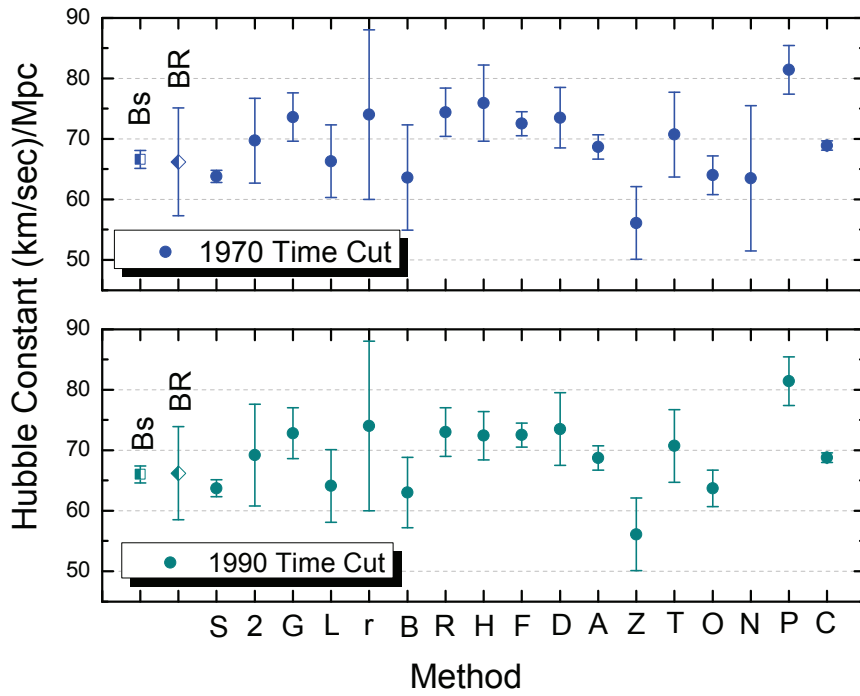Fig. 1.— Historical evolution of Hubble constant measurements.

Fig. 2.— Evaluated values of Hubble constant using 1970 and 1990 time cuts for experimental data. These plots include the evaluated or recommended values for combined observations, using the Best Representation (BR) and Bootstrap (Bs) data analysis techniques. Globular cluster luminosity function (G), Dn-Sig/Fund Plane (D), Novae (N), Planetary nebula luminosity function (P) results are also included while CMB Fit (C) value is shown for comparative purposes.

Table 1: Results of the Hubble Constant evaluation for all observations using 1970 and 1990 time cuts.

Method	Time Cut: 1970 (km/sec)/Mpc	Time Cut: 1990 (km/sec)/Mpc
Unweighted Average	67.56(73)	65.92(65)
Weighted Average	63.68(58)	63.87(51)
LWM	67.3(93)	66.08(64)
Normalized Residual	64.50(50)	64.33(48)
Rajeval Technique	65.57(45)	65.07(46)
Best Representation (BR)	66.2(89)	66.2(77)
Bootstrap (BS)	66.6(15)	66.0.(14)
Mandel-Paule	66.7(92)	65.3(62)